Wireless Sensor Networks Study for Real-Time Fruit Logistics Monitoring

Luis Ruiz-Garcia (1); Pilar Barreiro (1); José Ignacio Robla (2)

(1) Laboratorio de Propiedades Físicas y Tecnologías Avanzadas en Agroalimentación. Universidad Politécnica de Madrid. ETSI Agrónomos. Edificio Motores. Avda. Complutense s/n. 28040 Madrid. Spain

(2) Centro Nacional de Investigaciones Metalúrgicas. Consejos Superior de Investigaciones Científicas. Madrid. Spain.

Abstract

Progress in fruit logistics requires an increasing number of measurements to be performed in refrigerated chambers and during transport. Wireless sensor networks are a promising solution in this field. This paper explores the potential of this technology for monitoring fruit storage and transport conditions. It focuses in particular on ZigBee technology with special regard to two different commercial modules (Xbow and Xbee). The main contributions of the paper relate to the analysis of battery life under cooling conditions and the evaluation of the reliability of communications and measurements.

1. Introduction

Fruits and vegetables are submitted to a variety of risks during transport and storage that are responsible for material quality losses. As a consequence effective cold logistics monitoring is fundamental for ensuring product quality along the supply chain (Ruiz-Garcia *et al.*, 2007).

Wireless Sensors Networks (WSN) is a very promising technology in this field. A wireless sensor network is a system comprised of radio frequency (RF) transceivers, sensors, microcontrollers and power sources (Wang *et al.*, 2006). Instrumented with a variety of sensors, such as temperature, humidity and volatile compounds, WSN can be a solution for monitoring perishable food products in a distributed way (Callaway, 2004).

The use of wireless intelligent sensors inside refrigerated vehicles was proposed in 2004 by Qingshan *et al.*, (2004). Containers may incorporate a variety of sensors to detect, identify, log and communicate what happens during their journeys around the world. Jedermann *et al.*, (2006) presented a system for intelligent containers combining wireless sensor networks and RFID (Radio Frequency Identification). Ruiz-Garcia *et al.*, (2007) analyzed monitoring intermodal refrigerated fruit transport, facing the integration of wireless sensor networks with multiplexed communications and fleet management systems.

To date there has been no experimentation regarding fundamental factors in this field, such as node location inside the cargo, battery life and reliability of instrumentation under cooling conditions. Thus, experimentation in conventional refrigerated chambers could provide valuable information for near-future implementation in transports.

At the current stage there are two available standard technologies for WSN: ZigBee and Bluetooth. The ZigBee standard is built on top of the IEEE 802.15.4 standard. Both are within the Industrial Scientific and Medical (ISM) band of 2.4 GHz, which provides license-free operations, huge spectrum allocation and worldwide compatibility. ZigBee is more suitable for WSN, mainly because of its low power consumption derived from its multi-hop communication (Qingshan *et al.*, 2004; Wang *et al.*, 2006; Ruiz-Garcia *et al.*, 2007).

2. Objectives

The main objective of this paper is to study the performance of ZigBee motes for monitoring the refrigerated conditions in fruit chambers with low temperatures, high humidity and different cargo densities. Reliability of communications and measurements, together with battery life, are major issues in this work.

3. Materials and Methods

3.1. Commercial ZigBee motes

Two different types of ZigBee motes have been used: Crossbow (Xbow) and Xbee-PRO (Xbee). In both systems, one sensor node (transmitter), and one base station (receiver), has been tested.

The Xbow motes are integrated by a microcontroller board (Micaz) together with an independent transducer board (MTS420) attached by means of a 52 pin connector. The Micaz mote hosts an Atmel ATMEGA103/128L CPU running the Tiny Operating System (TinyOS). Micaz has a radio device Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4. The RF power in the Micaz can be set from -24 dBm to 0 dBm. Power is supplied by two AA alkaline batteries. For some of the experiments, two D type batteries were substituted.

The MTS420 board hosts a variety of sensors: temperature and relative humidity (Sensirion SHT), light intensity (TAOS TSL2550D), barometric pressure (Intersema MS5534B), two-axis accelerometer (ADXL202JE) and GPS (Leadtek GPS-9546) that can be easy removed. A laptop computer is used as the receiver, and communicates with the nodes through a Micaz mounted on the MIB520 ZigBee/USB gateway board; this device also provides a USB programming interface. For this paper, only Sensirion SHT sensors were used

The XBee-PRO RF module is a ZigBee/IEEE 802.15.4 compliant solution for WSNs. Advanced configurations can be implemented using simple AT commands (Hayes command set). According to the manufacturer, it uses 60 mW (18 dBm), 100 mW EIRP (Equivalent isotropically radiated power) power output (up to 1.6 km range).

Based on the Xbee-PRO development kit, we developed a prototype for monitoring. It includes an Xbee-PRO board, together with a development kit from a Sensirion SHT sensor; power for both came from a 12V 7Ah battery. This sensor measures temperature and humidity, using CMOS (Complementary Metal Oxide Semiconductor) technology, and is the same sensor installed on the Xbow motes.

3.2. Experiments

Two different types of experiments were conducted in order to verify the performance and reliability of ZigBee wireless nodes (see Table1). Some were carried out in an experimental refrigerated chamber (ERC); the remainders were conducted in a commercial store (CWC) in the wholesale fruit and vegetable market in Madrid.

For both experiments, the main parameters considered were the ratio of measurement losses (%), battery life (minimum), and the influence of node location and on/off operation of the cooling system. The reliability of measurements in relation to battery status was also considered.

The ERC has a capacity of 5.98 m3, and is made of metallic panels, with two engines. The WSN motes have been tested at the ERC with two battery types, two cargo levels, three different set points and at several locations inside the chamber (see Table 1).

Table 1: Summary of experiments

Experiment	**Description**	**Mote type**	**Battery type**	**Sample rate/ sensors**	**Set point**
ERC	Empty chamber, three positions sampled	Xbow	alcaline 2*AA	11s T, RH, GPS	0º C, 8ºC, 20ºC
			alcaline 2*D	11s T, RH, GPS	0º C, 8ºC, 20ºC
	Chamber loaded with 720 l of water, sampled inside and outside pallets	Xbow	alcaline 2*AA	11s T, RH, with and without GPS	0ºC
CWC	Chamber loaded with 13 pallets of chard, three positions sampled	Xbow	alcaline 2*D	11s T, RH, GPS	3ºC
		Xbee	Lead 12V 6Ah	10s T, RH	

Since temperature (T) and relative humidity (RH) conditions for fresh fruit during transport ranges from -0.5ºC to 12.2ºC and from 75 to 90%RH, in this study three different conditions within this range were selected: ambient conditions (20ºC approx.), 8ºC with 65% RH and

0ºC with 90% RH (see Table 1). This third situation corresponds to the optimal conditions for transporting many species such peaches or strawberries (GDV, 2005).

The influence of cargo density on communications reliability was evaluated at the ERC, comparing transmission through empty chamber with regard to nodes located inside/outside a pallet full of water bottles (720 l).

Experiments performed at CWC (1848 m3) make use of a chamber that provides on/off glycol cooling and which is insulated with polyurethane foam sandwiched between two layers of corrugated plate (total wall thickness is 0.16 m). The set point for this chamber was fixed at 3ºC by user restrictions. Tests were also conducted to measure the effect of different cargo densities, and to compare several ZigBee systems (Xbow and Xbee) under three different conditions: free space, 13 pallets full of boxes between the emitter and receiver, and emitter inside the sixth pallet in a line of 13. The second and the third situations simulate the implementation of wireless nodes inside refrigerated trailers, where the normal cargo situation is two lines of 13 Pallet EUR 2 (1 x 1.2 m) or three lines of 11 Pallet EUR (0.8 x 1.20 m) (ISO, 2003).

The program installed in the motes collects data from all the sensors at a fixed sample rate (11 s for Xbow; 10 seconds for Xbee), with each transmission referred to as a “packet.” Sample rate (SR) was fixed to provide very limiting conditions for battery life, a major issue in this study. In all the experiments, the RF power in the Xbow motes was set to 0 dBm.

3.3. Data analysis

A specialized MATLAB program has been developed for assessing the percentage of lost packets (%) in transmission, by means of computing the number of multiple sending failures. A multiple failure of m messages occurs whenever the elapsed time between two messages lies between 1.5 x m x SR and 2.5 x m x SR. For example, with a sample rate of 11 s, a single failure (m=1) occurs whenever the time period between consecutives packets is longer than 16.5 s (1.5x1x11) and shorter than 27.5 s (2.5x1x11). The total number of lost packets is computed based on the frequency of each failure type. Accordingly, the total percentage of lost packets is calculated as the ratio between the total number of lost packets and the number of sent packets.

The standard error (SE) associated to the ratio of lost packets is computed based on a binomial distribution.

4. Results

Tables 2 and 3 summarize the main results for the ERC and CWC experiments respectively. Results have been categorized into battery life assessment and communication and data reliability and will be presented accordingly in the text.

Table 2: Average percentage of packet looses for Xbow motes in ERC and corresponding standard error

	Cooling system		
	OFF	**ON**	
Transmitter location	**20ºC**	**8ºC 65%RH**	**0ºC 90%RH**
Lower corner	0.27%±0.06% (7256)* 0**	15.73%±0.52 % (4849)* 18**	0.50%±0.12% (3735) * 1**
60 cm. over the opposite corner	0.00%±0.00% (5482) * 0**	4.63%±0.31% (4515) * 19**	1.00%±0.18% (2876) * 1**
60 cm over the corner bottom	0.00%±0.00% (7180) * 0**	2.15%±0.23% (3848) * 15**	0.00% ± 0.0% (3149) * 1**

*Number of measurements. ** Number of on/off control cooling

Table 3: Average percent of packet looses and corresponding standard error for Xbow and Xbee motes at CWC. Number of measurements is included in brackets

Transmitter location	**Xbow**	**Xbee**
Empty room	1.38%±0.06 (34160)	0.00±0.00 (16906)
Trough 13 pallets	1.92%±0.07 (39225)	0.02±0.01 (18325)
Inside the boxes (pallet 6)	4.74%±0.15 (36614)	0.26±0.06 (15103)

3.1. Battery life

Figure 1 shows that battery life is clearly affected by temperature. Fisher´s F (F=19.9) shows that temperature has a significance in battery life. Thus for AA batteries the duration decreases from 610±83 minutes at 20ºC to 407±58 at 8ºC and to 297±44 minutes at 0ºC.

Life for D-type is on average 70% greater than for AA batteries, also with duration decreasing according to temperature from 655±145 minutes at 8ºC to 379±136 minutes at 0ºC (figure 2).

It is important to note that battery life for Xbow motes without GPS is extended up to 4500 min at 0ºC with 2AA batteries, while it falls below 300 minutes when a GPS device is mounted. Such heavy power consumption will be further discussed in relation to heat dissipation.

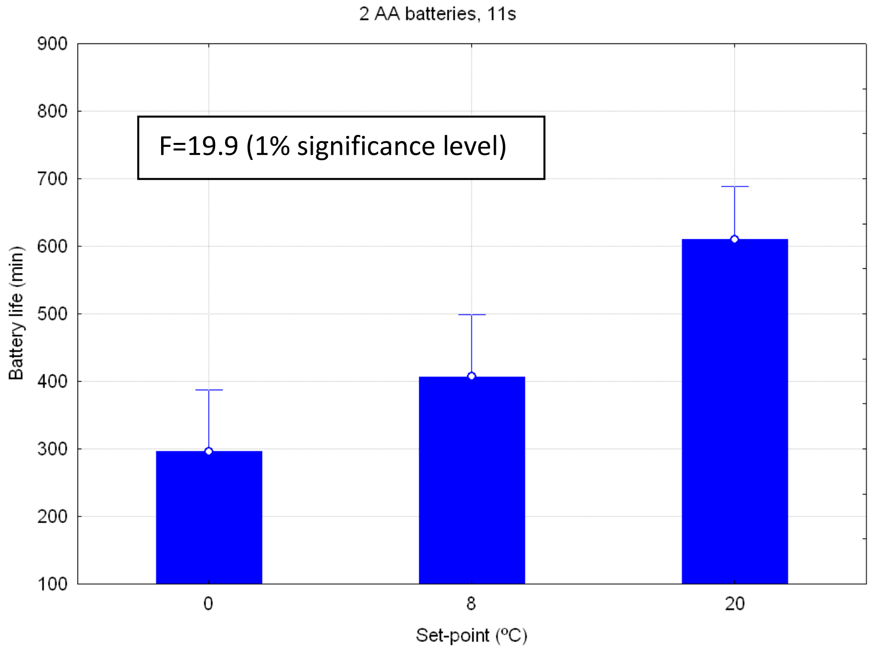


Figure 1: Average battery life for different set-points during the experiments in ERC for 2AA batteries at 11s sample rate

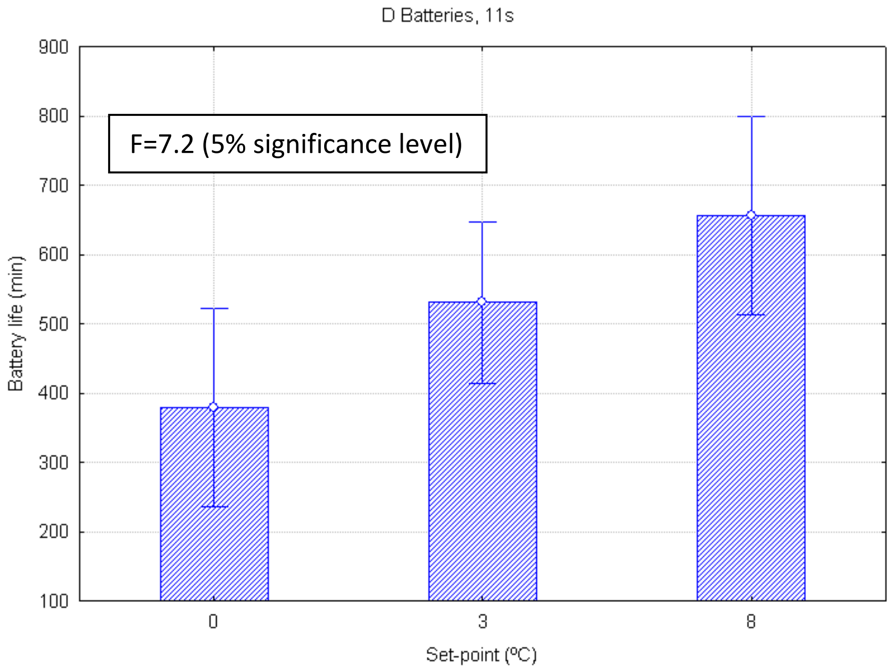


Figure 2: Average battery life for different set-points during the experiments in CWC with 2D batteries at 11 s sample rate

3.2. Communication reliability

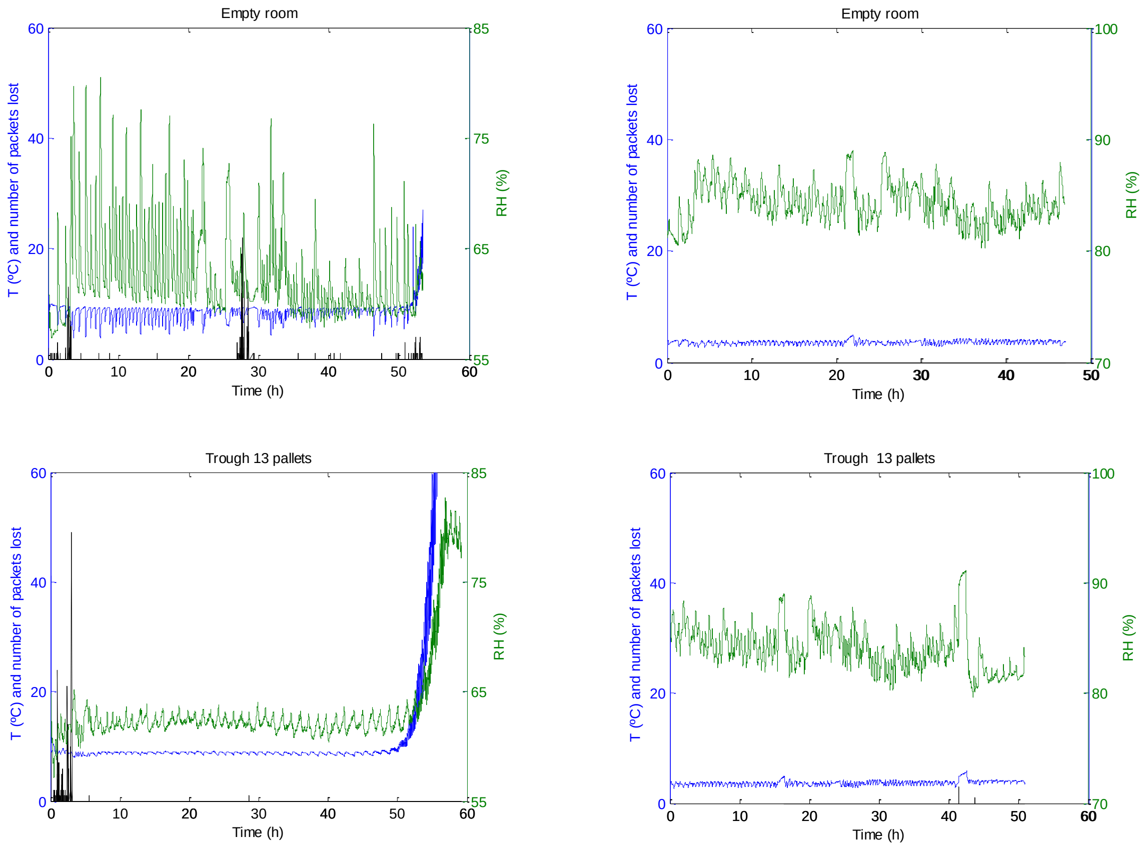
In the experiments carried out at ERC, the percentage of lost packets was always higher at 8ºC (2.15%-15.73%) than at 0ºC (below 1%) or 20ºC (below 0.27% Table 2). This fact seems to be related with the number of on/off operations of the cooling system: none for 20ºC, 1 for 0ºC and between 15 and 19 for 8ºC.

Table 3 shows the results obtained for the experiments conducted at CWC. Xbee motes performed better than Xbow in terms of reliability of communications; a lower ratio of lost packets was found at all locations for Xbee compared to Xbow. In both cases (Xbow and Xbee), no restrictions were found for signal propagation along 13 pallets, even though the rate of lost packets was higher in this situation compared to an empty room. The highest ratio of lost packets was found when the mote was located inside the cargo (emitter inside pallet 6), reaching as high as 4.74% for Xbow motes. Note that this value is lower than the 15% found for ERC; the greater amount of free space at CWC compared to ERC could be the basis of such a difference.

3.3. Data reliability

Data reliability is a critical issue for ensuring interest in future implementations of this technology within transportation.

Figure 3 compares the time evolution of T (ºC) and RH (%) for Xbow and Xbee motes at CWC experiments. Generally RH varies inversely to T; only for door openings were there a simultaneous increase in T and RH due to hot air entering from outside. A major difference between Xbow and Xbee concerns the order of magnitude in T and RH which stayed around 8ºC and 60% RH for Xbow while being around 3.5ºC and 85% for Xbee (set-point of the chamber was 3ºC). This is a puzzling question since both sensors are the same and came calibrated from the manufacturer. At high T, RH decreases and that would explain the lower order of magnitude for RH at Xbow compared to Xbee. The high energy consumption of the GPS could be the cause of heat dissipation and the T increase for the Xbow mote.



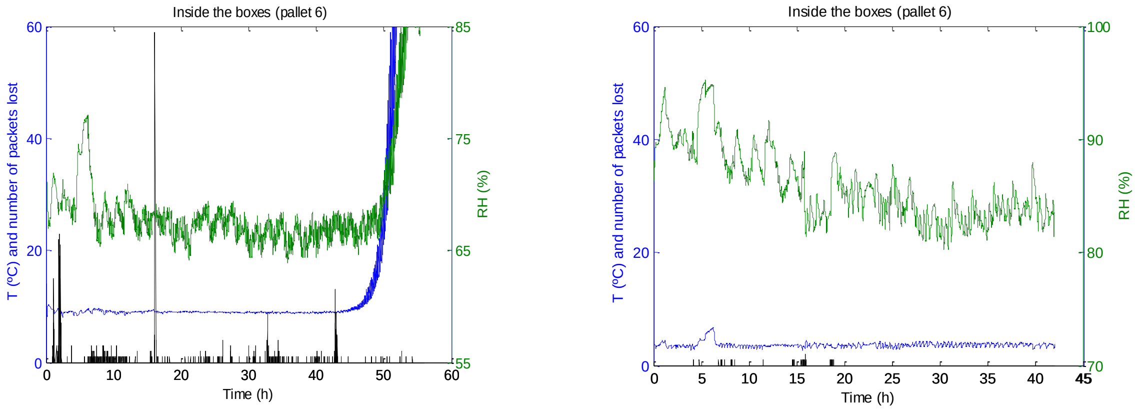


Figure 3: RH (%), T (ºC) number of data lost packets for Xbow (left column) and Xbee (right column) in CWC.

Figure 3 shows that for the Xbow motes, T (ºC) and RH (%) measurements become erroneous at low battery voltage. This occurred around 2160 mV in all experiments. T (ºC) rises enormously and both RH (%) and T (ºC) increase in variability.

Table 4 indicates the battery voltage threshold at which T and RH measurements lost their reliability (between 2159-2167 mV). Table 7 compares the average and standard deviation of T and RH for both Xbow and Xbee motes.

Table 4: Battery conditions for abnormal T, HR measurements with Xbow motes in CWC

	Parameters at initial failure		**Parameters at failure stabilization**	
	Battery life (h)	**Voltage (mV)**	**Battery life (h)**	**Voltage (mV)**
Empty room	51.2	2163.0	-	-
Trough 13 pallets	49.9	2166.7	57.5	2094.2
Inside pallet 6	46.6	2159.2	54	2070

6. Conclusions

In this paper, the feasibility of using two types of wireless nodes (Xbee and Xbow) for monitoring storage and transport was experimentally assessed. Both ZigBee motes perform adequately under typical T and RH conditions in the cold supply chain. The suitability of this technology for monitoring refrigerated chambers as well as the implementation under transport conditions has been demonstrated. These sensors can be placed in locations usually not accessible for other systems.

Battery life decreases under cooling conditions. For 2xAA batteries in a GPS Xbow mote, life at 0ºC (297±44 min) is half than that at 20ºC (610±83 min), increasing to 379±136 min for 2xD batteries at 0ºC. When the GPS device is removed from the mote, battery life is extended by a factor of ten.

Measurements for Xbow sensors become erroneous when the battery voltage is less than 2160 mV regarding to 3000 mV corresponding to full charge. Further research is necessary, for programming algorithms in order to save energy and to extend battery life. The on-board identification of erroneous measurements is basic for commercial purposes and has been outlined in this paper.

Xbee motes could be a good solution for wireless monitoring in refrigerated industrial environments, because the rate of lost packets inside the cargo (0.26%) is always lower than that of Xbow (4.74%). For the latter, a large quantity of lost packets is found at singular moments, which never occur for Xbee motes. The better reliability of the Xbee motes corresponds with their higher RF power. However, a potential concern in the Xbee based prototype is the large battery size, which makes the system much bigger than the Xbow motes.

The performance of the system can be improved by the implementation of advanced network topologies, such as point-to-multipoint, peer-to-peer and mesh, improving the reliability and robustness of the system. It is important to optimize the performance of every component (sensors, microcontrollers and radiofrequency devices) to consume as little power as possible while still meeting the requirements of the application in terms of data throughput, latency and reliability.

Another important topic is fault detection and isolation. The detection of failures in a wireless network is fundamental. For Xbow motes, automated detection of erroneous measurements is addressed on the basis of abnormal oscillations of measurement. A large effect of the GPS device on dissipation and temperature measurements is found whenever the T and RH sensor is not properly located in the mote.

Acknowledgements

Thanks to the SENSOFRIGO research program supported by the Ministry of Education and Science of Spain (Ref: AGL2003-06073-C02-01) and TAGRALIA project funded by the Comunidad de Madrid. The authors would like to thank also Alejandro Navarro, Pablo Poncela and Jorge Sánchez for their help in the experiments.

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